Higgs Width Determination Using ZHZZ* Events in Six Jets Final State

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Link to previous updates

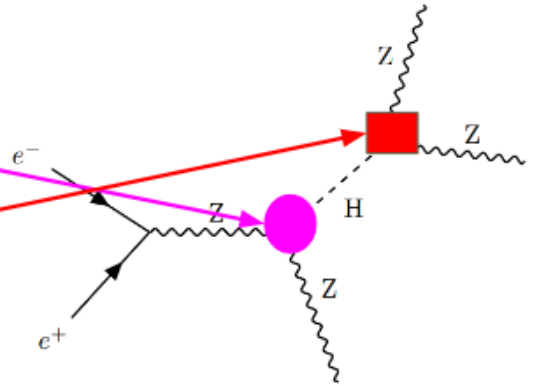
This update is in continuation of my updates:

- https://indico.cern.ch/event/1304164/#20-hzz-in-6jets-events
- https://indico.cern.ch/event/1327332/#25-hzz-in-6jets-events

Higgs Decay Width measurement with ZHZZ*

- One of the ways to determine the Higgs width at Lepton collider could be as follows:
- In the process $e^+e^- \to ZH$

$$\sigma(e^+e^- \to ZH) \propto g^2_{HZZ}$$



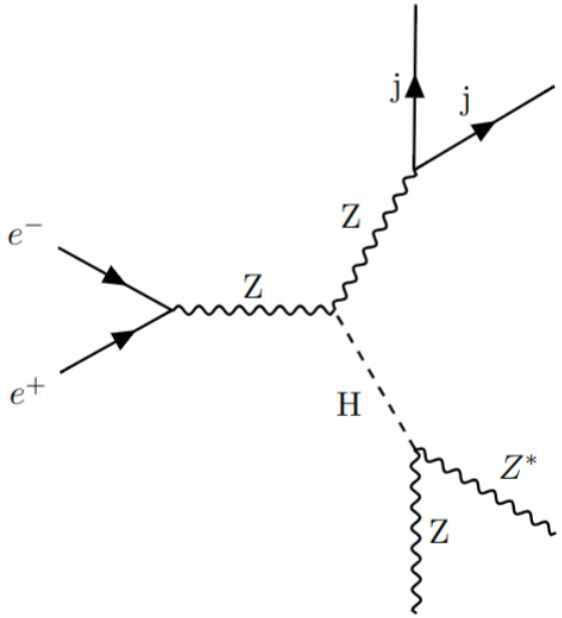
- Also:

$$Br(H \to ZZ^*) = \frac{\Gamma_{H\to ZZ^*}}{\Gamma_H} \propto \frac{g^2_{HZZ}}{\Gamma_H}$$

- Combining the above equations:

$$\sigma(e^+e^- \to ZH) \times BR(H \to ZZ^*) \propto \frac{g^4_{HZZ}}{\Gamma_H}$$

Signal Process



Cross-Section = 0.0017 pb

- Signal process considered in this study is $e^+e^- \rightarrow Z(\rightarrow jj)H(\rightarrow Z(\rightarrow jj)Z^*(\rightarrow jj))$
- The six jets that we consider in the study orignate from the decays of Z bosons.
- Cross-section of the process, including decay widths, at 240 GeV at FCCee is 0.0017 pb.
- The signal event yield is:

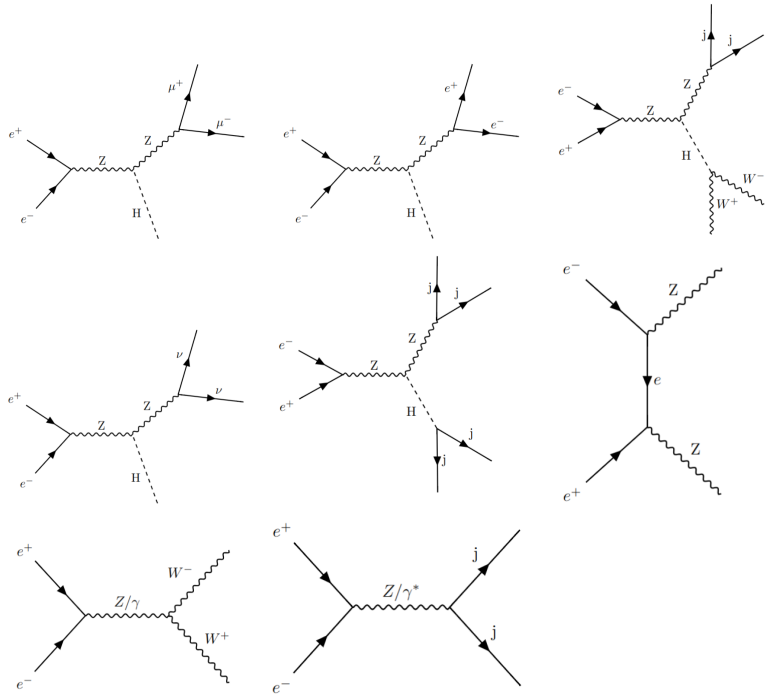
$$N_{ZHZZ^*(6\,j)} = \sigma_{e^+e^-\rightarrow ZH} \times Br(H \rightarrow ZZ^*) \times (Br(Z \rightarrow jj))^3 \times \mathcal{L}$$

$$\approx 0.2(\text{ pb}) \times 0.025 \times (0.7)^3 \times 5.10^6(\text{pb}^{-1}) \approx \mathbf{8575}$$

Background Processes

- Processes consisting 2, 4 or 6 jets in the final state and not belonging to the aforementioned signal process are considered as background processes.

Process $e^+e^- \rightarrow$	σ (pb)	Yield (Yield wrt. signal)
$Z(\mu^+\mu^-)H$	0.0067	3.38×10^4 (1.8)
$Z(e^+e^-)H$	0.0071	3.58×10^4 (1.9)
$Z(jj)H(WW^*)$	0.031	1.54×10^5 (8.1)
$Z(\nu\nu)H$	0.046	2.30×10^5 (12.2)
$Z(jj)H(jj)$	0.108	5.42×10^5 (28.6)
ZZ	1.359	6.79×10^6 (358.9)
WW	16.439	8.22×10^7 (4341.5)
$Z(qq)$	52.654	2.63×10^8 (13906.1)



Preselection Cuts on Events

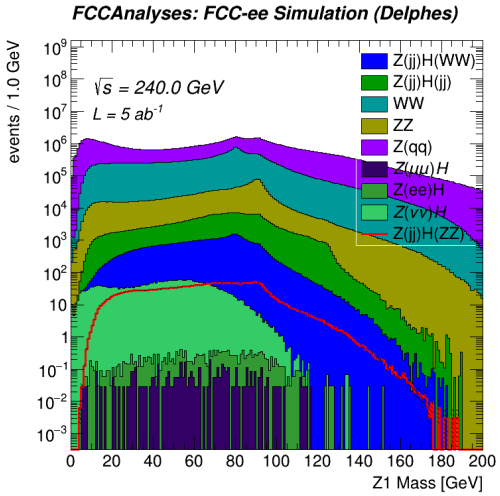
- **Orthogonal selection cuts** Applied at Stage 1 of analysis to remove events with either leptons or significant missing energy:
  - Missing Momentum < 20 GeV
  - Electron and Muon Momentum < 10 GeV
  - Number of jets = 6 (used for cutflow as well)

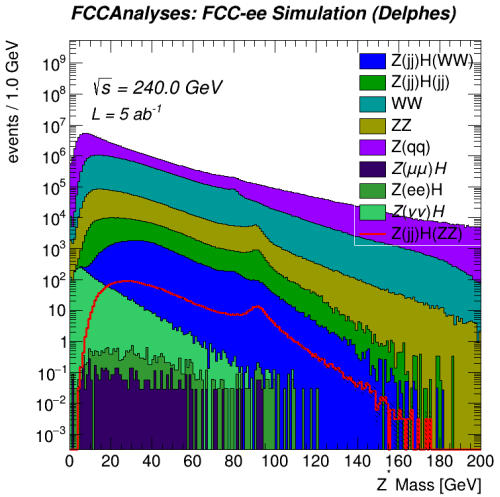
Reconstruction Strategy

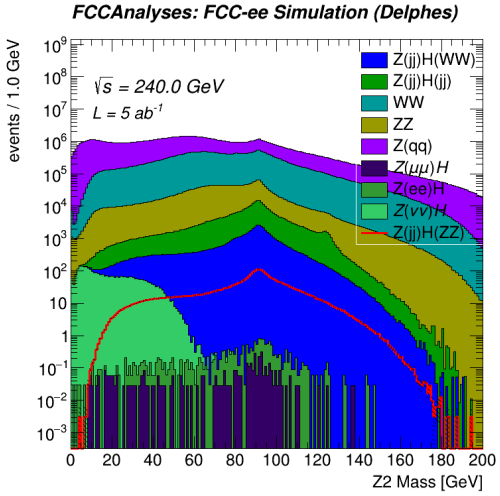
Require: $N_{\text{jets}} = 6$ and other pre-selection cuts

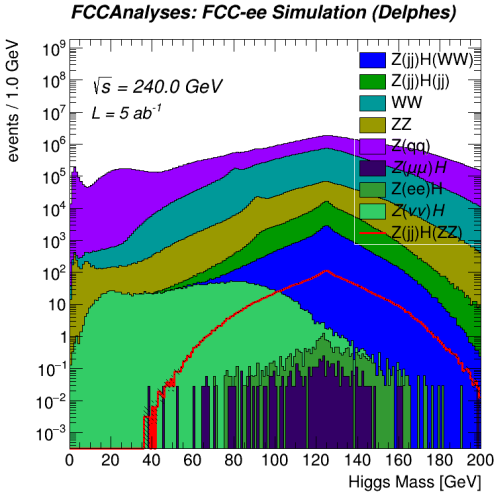
1: Consider all possible combinations of choosing two jets out of six jets (${}^6C_2 = 15$);
2: Find a pair of jets whose mass is most consistent with the mass of Z boson (91 GeV) and whose combined jet flavour probability is greater than 1.2 for b-jets, 1.0 for c-jets, and 0.8 for s-jets;
3: Label the two jets found above as Z1 boson and discard them from the temporary jet collection;
4: The temporary jet collection now contains four jets, and we can form ${}^4C_2 = 6$ combinations of jets;
5: Again find a pair of jets whose mass is most consistent with the mass of Z boson (91 GeV) and whose combined jet flavour probability is greater than 1.2 for b-jets, 1.0 for c-jets, and 0.8 for s-jets;
6: Label this jet pair as Z2 boson;
7: We now have two jets (${}^2C_2 = 1$); Hence label the remaining two jets as Z^* boson. (No flavour probability requirements at this stage.)
8: Combine the Z1 and Z2 bosons with Z^* boson one-by-one to check which combination is consistent with the Higgs mass (125 GeV);
9: The other Z boson is then assumed to be coming from ZH process;
10: **Relabelling**: The Z boson used to reconstruct Higgs boson is relabelled as Z1 and other Z boson from ZH hard process is relabelled as Z2 boson;

Reconstruction of Z and Higgs Boson



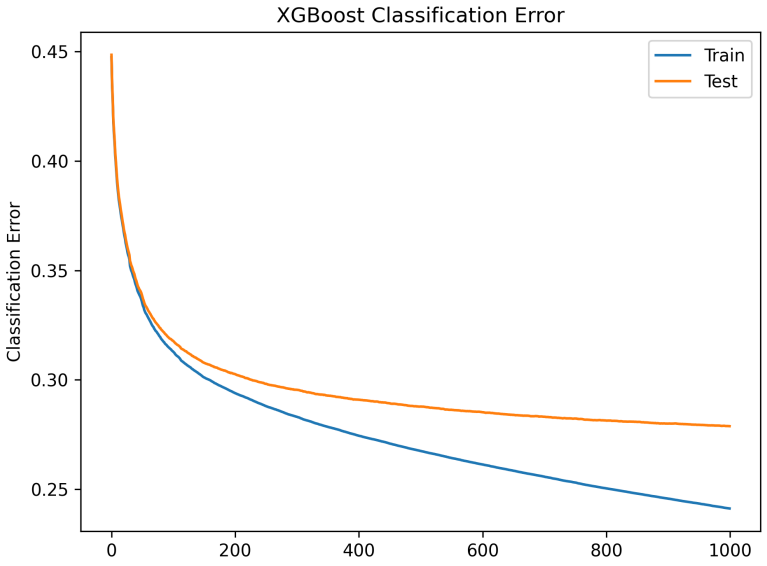


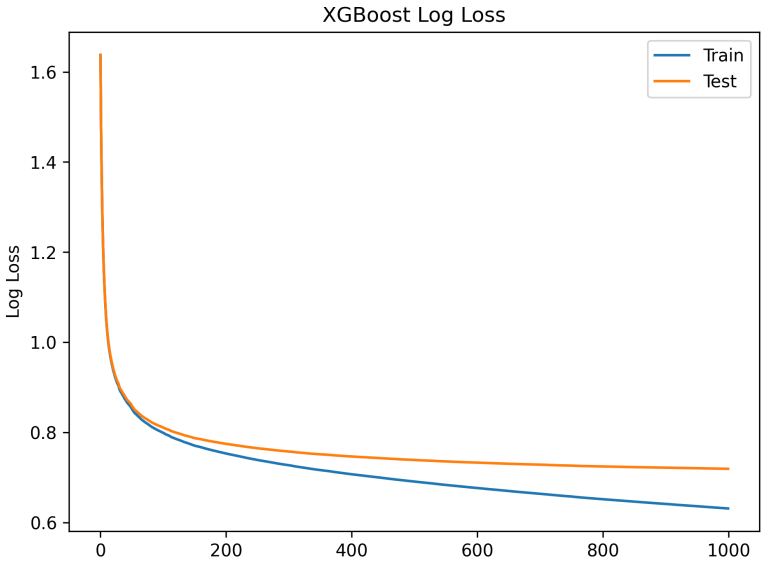




Machine Learning Setup: Discriminating Signal from background

- We used BDT within XGBoost framework to train and evaluate the ML model.
- XGBClassifier is used to classify events as either ZHZZ, ZHWW, ZjjHjj, ZZ, WW, Zqq, Lepnu
- "multi:softprob" is used as an objective function
- 1000 estimators (trees) are used for the BDT



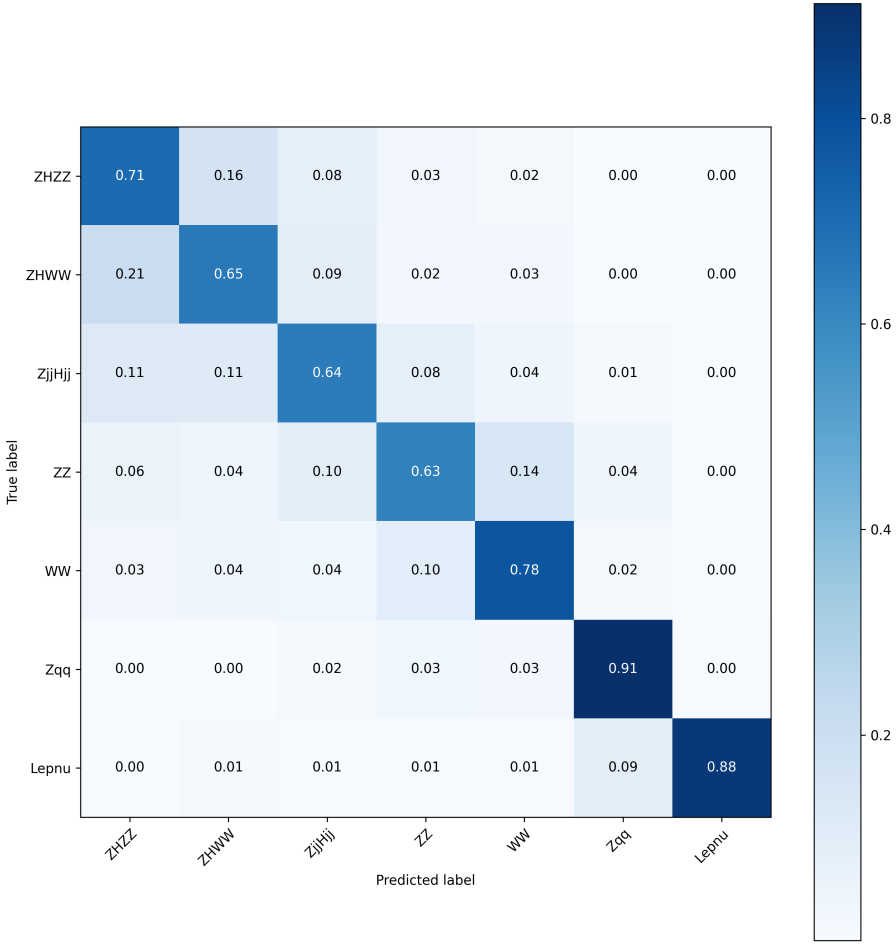


Machine Learning Setup: Input Variables

- To train the BDT we have used the following variables. Note that no additional cuts are applied at this stage.

Name	Total Variables
Jet P, E, ϕ, θ	$6 \times 4 = 24$
Jet flavour variables (B/C/S/Q/G)	$5 \times 6 = 30$
$\sqrt{d_{23}}, \sqrt{d_{34}}, \sqrt{d_{45}}, \sqrt{d_{56}}$	4
$p_T^{vis}, M^{vis}, E^{vis}, P^{miss}$	4
Z_1, Z_2, Z^* - M, P, E, θ, ϕ	15
Higgs - M, P, E	3
$\Delta R_{Z1,Z^*}$, $\Delta\phi_{Z1,Z^*}$, $\Delta\theta_{Z1,Z^*}$	3
$\Delta R_{Z2,Z^*}$, $\Delta R_{Z1,Z2}$	2
Total	85

Machine Learning Outcome



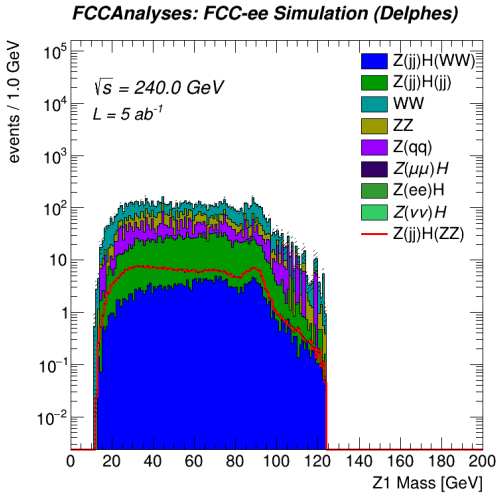
- The output variable from Machine Learning evaluation is $\log_{10}(\frac{p_{ZHZZ}}{1-p_{ZHZZ}})$ where p_{ZHZZ} is the probability that a given event is signal (ZHZZ).
- A cut applied on this variable then distinguishes ZHZZ from the background samples

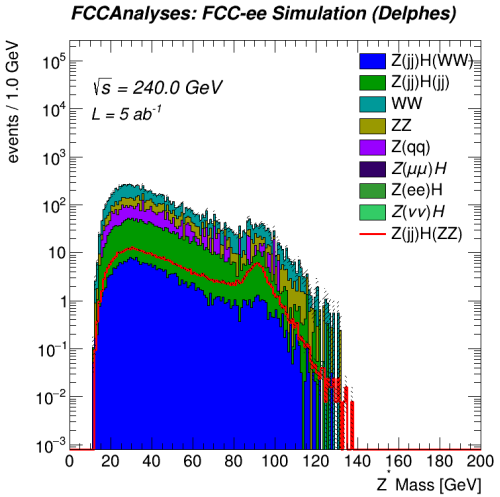
Results from Cutflow

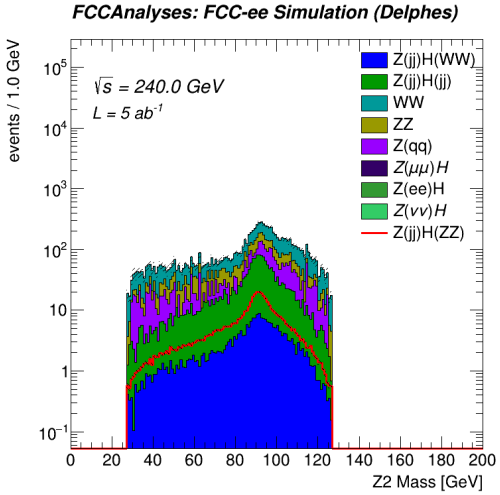
- After machine learning outcome, we carry out a cut and count based analysis.

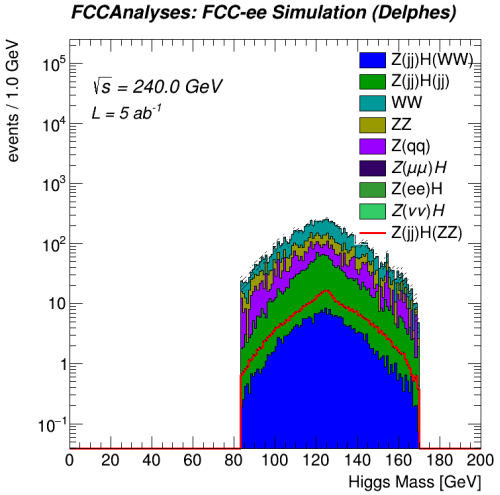
Cuts	$Z(jj)H(ZZ^*)$	$Z(jj)H(WW^*)$	ZZ	WW	$Z(jj)H(jj)$	$Z(qq)$	$Z(\mu\mu)H$	$Z(ee)H$	$Z(\nu\nu)H$	$S/\sqrt{S+B}$	S/B
Preselection	7856	65816	2507763	33235869	333237	93181865	4	16	3263	0.691	0.0001
$E^{\text{vis}} > 198$	7850	64258	2474113	32956089	329449	86607070	3	16	0	0.709	0.0001
$M^{\text{vis}} > 9$	4895	40359	493511	4531373	158671	2985837	0	0	0	1.708	0.0006
$\sqrt{d_{23}} > 47$	4512	37402	432753	3870367	140241	1540859	0	0	0	1.838	0.0007
$\sqrt{d_{34}} > 23$	4146	34873	330750	2875005	119876	708174	0	0	0	2.055	0.001
$\sqrt{d_{45}} > 15$	3464	30714	173191	1415771	70442	293604	0	0	0	2.458	0.0017
$\sqrt{d_{56}} > 10$	2691	24923	85023	665615	37389	140879	0	0	0	2.752	0.0028
$83 < m_H < 170$	2661	24716	83413	644056	37125	135001	0	0	0	2.764	0.0029
$11 < m_{Z1} < 124$	2656	24694	83201	641263	37078	133737	0	0	0	2.766	0.0029
$27 < m_{Z2} < 127$	2608	24367	80700	610851	36520	126248	0	0	0	2.778	0.003
$m_{Z*} > 11$	2608	24367	80700	610850	36520	126248	0	0	0	2.778	0.003
$23 < E_{Z1} < 136$	2605	24356	80602	609985	36500	125727	0	0	0	2.778	0.003
$50 < E_{Z2} < 133$	2595	24286	80175	605199	36353	124452	0	0	0	2.778	0.003
$ZHZZ > 0.59$	494	251	1801	3882	1627	1653	0	0	0	5.014	0.0536
Cumulative Efficiency	0.05%	0.005%	0.006%	0.003%	0.022%	0.003%	0.0%	0.0%	0.0%	5.01	0.0536

Reconstruction of Z and Higgs Boson after cuts









Outlook and Next Steps

- We used Machine Learning to distinguish signal from background
- The current signal significance computed using $S/\sqrt{S+B}$ is 5.01.
- In this update the light flavour jets were ignored altogether at the reconstruction step. However, in the next iteration we would like to see the impact of including light-flavoured (u and d) jets.
- Variables such as invariant jet masses and angular distances between jets will be added as an input to the Machine Learning setup.
- Additionally the cutflow table will also be improved.
- The Major Step To Do is to implement this analysis within boost-hist combine statistical framework and work to do so is currently ongoing.